

1 COMPENSATING FOR DRIFT AND SENSOR PROXIMITY IN A SCANNING
2 SENSOR, IN COLOR CALIBRATING INCREMENTAL PRINTERS

6 RELATED PATENT DOCUMENTS

8 Related documents include other, coowned U. S. utili-
9 ty-patent documents hereby incorporated by reference in
10 their entirety into this document. One is in the names of
11 Francesc Subirada et al. and filed, very generally concu-
12 rently with the present document, under attorney docket
13 code 60990045Z142 — and later assigned application serial
14 09/____,____ and issued as U. S. Patent 6,____,____. Anoth-
15 er is in the names of Thomas Baker et al. and is applica-
16 tion serial 09/183,819, later issued as U. S. 6,____,____.
17 Yet another is in the name of Antoni Gil Miquel, serial
18 09/642,417, issued as U. S. 5,____,____.

22 FIELD OF THE INVENTION

24 This invention relates generally to inexpensive ma-
25 chines and procedures for incremental printing of text or
26 graphics on printing media such as paper, transparency
27 stock, or other glossy media; and more particularly to de-
28 tails of operating a scanning sensor for color calibration
29 in such economical machines and procedures.

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1 BACKGROUND OF THE INVENTION

2
3 (a) Color calibration — Color reproduction is
4 affected by printer variables, which can include different
5 drop volumes of different pens, firing energies from the
6 printer system itself, and kinds of media. Manufacturing
7 tolerances, often quite broad — in the interest of econ-
8 omy — in these and other printer parameters result in a
9 deviation between the actual and the targeted color.

10 To correct such deviations, it is known to include in
11 a printer an automatic color-calibration algorithm, which
12 can compensate for these differences. The idea is to cal-
13 ibrate the printer so that it acts as a nominal printer.

14 A representative approach to such corrections in-
15 volves transfer functions (Fig. 1) preferably in the form
16 of one-dimensional lookup tables (LUTs) — one transfer
17 function for each channel (cyan C, magenta M, yellow Y and
18 black K). Each transfer function is intended to perceptu-
19 ally linearize the response of the corresponding channel.

20 Preparing such transfer functions necessarily begins
21 with some form of comparison between the actual output and
22 the ideal output of a printer, in response to a known in-
23 put. Such comparison in turn calls for printing a test
24 pattern and then measuring it colorimetrically (or at
25 least "pseudodensitometrically", as defined in the above-
26 mentioned patent document of Thomas Baker) — in general a
27 well-known procedure, with many variants.

28 Many incremental printers have a so-called "line sen-
29 sor" that is mounted with the marking devices ("pens" in
30 an inkjet machine) and typically provided for facilitating
31 mechanical enhancements such as pen alignment. Line sen-
32 sors have been found adequate for simple densitometric
33 measurements and accordingly in many printers are now com-
34 monly put into service for color calibration as well. The

1 Baker document includes extensive orientation to such sen-
2 sors and their pseudodensitometric use, and related ways
3 of alternatively obtaining more-precise measurements for
4 calibration, e. g. through use of an onboard colorimeter.
5

6 (b) Linearity and stability — In all such efforts
7 it is necessary to confront certain sources of measurement
8 inaccuracy and imprecision. Virtually all equipment used
9 for such measurements is subject to displacements of both
10 measurement zero and range; and such measurement displace-
11 ments must be carefully controlled to avoid collecting
12 meaningless data. (Here the word "range" does not mean
13 distance, but only means a tonal or colorimetric interval
14 between zero and full-scale.)

15 Displacement of the measurement zero point is common-
16 ly and adequately managed by taking a reading without il-
17 lumination. Range displacement most typically is more
18 difficult to bring under control because it implicates the
19 linearity and stability of every element — optical, elec-
20 tronic and mechanical — in the signal train.

21 Linearity is a requirement for sensitivity and accu-
22 racy (absolute correctness of what is measured). Stabili-
23 ty is a requirement for precision (reproducibility) — and
24 for accuracy too, as numbers can hardly be accurate if
25 they are uncertain.

26 In particular the optical part of the signal path be-
27 gins with illumination, i. e. the light source. This part
28 of the path also extends, through the visual/mechanical
29 properties of the printing medium, to the detector and the
30 optoelectronic conversion which it performs.

31 The electronic part of the signal path begins with
32 electronics that drive the light source, and picks up
33 again where the detector hands off an analog electrical
34 signal to (modernly) an analog-to-digital converter (ADC).

1 Even though the illumination end of the train requires
2 only a single stable level, drift in the source excitation
3 or its electrooptical conversion efficiency is a severe
4 limitation — but usually accommodated satisfactorily by
5 allowing time for the source to warm up completely before
6 measurements begin.

7 At the other end of the optical train, the detector
8 and ADC too are subject to drifts but these are normally
9 under control when the source drifts are. The detector
10 and its ADC nevertheless have the far greater challenge of
11 responding not just at a single level but linearly over
12 the full possible range of the optical signals from the
13 test pattern.

14 Linearity here is essential, since the whole point of
15 the calibration — as mentioned above — is to develop a
16 compensation for perceptual nonlinearity in the printing
17 system. This requires that the detector and ADC be capa-
18 ble of sensitively discriminating and quantifying very
19 small differences in signal level, and these small differ-
20 ences are necessarily measured superimposed upon some
21 fairly substantial absolute level.

22 In other words, the measurement system must be able
23 to quantify small differences between big numbers, and
24 this ordinarily calls for high-quality, very sensitive and
25 linear equipment. The computer-printer field, however, is
26 extraordinarily price-competitive — and a detector and
27 ADC of such quality are costly.

28
29 (c) Secondary standard — A known approach to miti-
30 gating the demands on these measurement elements is to
31 provide a reference measurement at or near the full-scale
32 level of the measuring system, so that at least the range
33 itself is well defined. Thus it is commonly known to
34 expose the detector to the printing medium, in a region

1 that has no printing — i. e. that is bare printing medium
2 — shortly before using the detector to make color mea-
3 surements of a test pattern.

4 When this is done, the sensor system need not be it-
5 self a good absolute standard but only a secondary stan-
6 dard, since it is referred to the optical reference.

7 Again, this approach mitigates, but does not eliminate,
8 demands on the measurement elements.

9 This strategy still depends upon linearity in the de-
10 tector and ADC. These devices are ordinarily adequate in
11 linearity, provided that the d. c. level (the pedestal on
12 which the small signal differences are superposed) is not
13 excessively high; and provided also that the warmup period
14 mentioned above is sufficient for good stability in the
15 lamps, detector and ADC.

16
17 (d) Linearity and cost — In one concurrently devel-
18 oped system (not prior art), it has been found that these
19 requirements can be met if the ADC is a relatively expen-
20 sive unit. One key reason for this expense is that the
21 d. c. signal pedestal is in fact quite elevated, placing
22 stringent demands on sensitivity of the ADC, and this rea-
23 son in turn arises — interestingly enough — directly
24 from spectral requirements on the light source, as will
25 now be explained.

26 In these systems it is necessary to use lamps that
27 provide good illumination throughout the visible spectrum,
28 since the inks in use necessarily span all those colors.
29 Favored sources nowadays are light-emitting diodes (LEDs),
30 and it is necessary to use two such devices to cover the
31 visible colors. An LED, like most lamps, is notoriously
32 temperature dependent in emission intensity, spectral dis-
33 tribution, and in some cases even spatial distribution of
34 intensity across the beam.

1 In practice to achieve sufficient warmup for the nee-
2 ded stability, both LEDs must be turned on continuously
3 throughout the measurement of the entire test pattern.
4 Therefore even when the detector and ADC are measuring
5 linearity for a particular ink that requires light from
6 only one lamp, the other lamp is running too.

7 Thus the sensor and ADC are forced into use in an
8 unfavorable mode: the small differences are as small as
9 always, but the "large number" (the d. c. level) is gen-
10 erally doubled. Although this difficulty has been couched
11 in terms of the LEDs currently favored, a similar unfa-
12 vorable relationship would arise even for a single, spec-
13 trally continuous source.

14 As noted above, this relationship has been found ac-
15 ceptable if an adequately linear ADC is in use, but this
16 condition requires a relatively costly ADC. In the con-
17 currently developed system mentioned above, the ADC is a
18 very sensitive twelve-bit unit. Such cost can be made
19 acceptable in a high-end system, but in a more economical
20 printer is very undesirable.

21 Thus the problem to be solved is how to provide sig-
22 nal linearity and sensitivity or "discrimination", ade-
23 quate for a good color calibration — more economically.
24 An inexpensive ADC would suffice if the required linearity
25 were not so high — in particular, if the signal pedestal
26 could be roughly halved — and this would be the case if
27 the light level were lower.

28 Full spectral illumination with adequate warmup, how-
29 ever, call for a high light level as described above. Ac-
30 cordingly a solution to the stated problem heretofore has
31 been elusive.

32
33 (e) Sensor proximity — Surprisingly, even the
34 above-mentioned concurrently developed high-end system,

1 notwithstanding its relatively higher cost, has been found
2 to exhibit a peculiar kind of instability in the calibra-
3 tion process. In this system as already noted the ADC is
4 quite sufficiently linear to enable full preliminary
5 warmup of light sources and operation with optical signals
6 that are superposed on a large pedestal as outlined in the
7 preceding subsection.

8 Nevertheless, despite amply adequate sensor stability
9 per se, accurate calibration has been found elusive in
10 this system. Upon careful analysis, what at first seemed
11 to be an entirely erratic measurement offset — varying
12 during the course of the calibration measurements — was
13 traced to a systematic variation with the tonal level be-
14 ing measured.

15 Although systematically related to tonal level, the
16 variation was not proportional to the tonal level but nev-
17 ertheless was correlated with particular tonal values. In
18 due course it was discovered that the correlation actually
19 was with position of the sensor-holding carriage along its
20 scan path — and, finally, with variations ("runout") in
21 the distance of the sensor from the printing medium, dur-
22 ing the scanning motion.

23 In other words, the sensor-to-medium distance varies
24 systematically along the scan axis. In retrospect this is
25 not entirely surprising, since the scan path over the
26 printing medium is nearly 1½ m (five feet) long and the
27 sensor runout quite tiny.

28 Nevertheless these minuscule displacements are more
29 than sufficient to cause major fluctuations in light re-
30 flected from the printing medium to the detector. Partic-
31 ularly awkward is a distinct nonlinearity of these dis-
32 placements, and of the resulting optical fluctuations,
33 with position along the scan axis. What is called for is

1 some means of compensating for this curious source of cal-
2 ibration error.

3
4
5
6 (f) Conclusion — As this discussion shows, limita-
7 tions of linearity, stability and price in economical sys-
8 tems — and also of mechanical tolerances in even a rela-
9 tively expensive system — continue to impede achievement
10 of uniformly excellent color calibration and therefore
11 inkjet printing. Thus important aspects of the technology
12 used in the field of the invention are amenable to useful
13 refinement.

14
15
16
17 SUMMARY OF THE DISCLOSURE

18
19 The present invention introduces such refinement. In
20 its preferred embodiments, the present invention has sev-
21 eral aspects or facets that can be used independently, al-
22 though they are preferably employed together to optimize
23 their benefits.

24 In preferred embodiments of a first of its facets or
25 aspects, the invention is a method of correcting for sen-
26 sor drift, in color calibration for a printer. The method
27 includes the step of printing on a printing medium a test
28 pattern for each of at least one colorant.

29 It also includes scanning a sensor, along a scanning
30 direction, over each test pattern and at least one adjoin-
31 ing tonal reference area of the medium. The phrase "tonal
32 reference area" means an area which is visible to the sen-
33 sor and for which a correct sensor response is known.

1 The printing step includes disposing each test pat-
2 tern next to — along the scanning direction — the "at
3 least one" reference area. Thereby the scanning step in-
4 cludes exposing the sensor to each respective reference
5 area, along the scanning direction.

6 The method also includes the step of interpreting the
7 sensor response to each reference area. The purpose of
8 this interpreting is to adjust the sensor response to at
9 least one part of each test pattern.

10
11 The foregoing may represent a description or defini-
12 tion of the first aspect or facet of the invention in its
13 broadest or most general form. Even as couched in these
14 broad terms, however, it can be seen that this facet of
15 the invention importantly advances the art.

16 In particular, by scanning a tonal reference, togeth-
17 er with the pattern — in the same scanning step — this
18 aspect of the invention is able to make a real-time ad-
19 justment to the sensor response. The sensor response
20 therefore can drift without impairing the accuracy of the
21 color calibration.

22
23 Although the first major aspect of the invention thus
24 significantly advances the art, nevertheless to optimize
25 enjoyment of its benefits preferably the invention is
26 practiced in conjunction with certain additional features
27 or characteristics. In particular, preferably the print-
28 ing step includes disposing each test pattern between
29 (still along the scanning direction) at least two of the
30 reference areas. If this first basic preference is ob-
31 served, then another preference is that at least two of
32 the reference areas be unprinted areas of the medium.

33 Another basic preference is that the at least one
34 reference area be an unprinted area of the medium. In any

1 event it is also preferred that the printing step include
2 printing the test pattern for each of plural colorants. A
3 more specific preference is that the printing step include
4 printing the test pattern for each of plural colorants in
5 succession.

6 Yet another basic preference is that the printing
7 step include printing as each test pattern a sequence of
8 color patches at various tonal levels — and that the in-
9 terpreting step include applying the sensor unprinted-area
10 responses to adjust the sensor response to substantially
11 each color patch in at least one of the plural test pat-
12 terns. In this case, it is further preferable that the
13 applying step includes applying the sensor unprinted-area
14 responses to adjust the sensor response to substantially
15 each color patch in substantially all of the plural test
16 patterns.

17 When the above-described applying step is performed,
18 it also preferably includes interpolation between two sen-
19 sor unprinted-area responses obtained at ends of each se-
20 quence of patches. In this case preferably the interpola-
21 tion is based upon an interpolation model that is either
22 an assumed mathematical function interrelating the re-
23 sponses at the ends of each sequence, with scan positions
24 within each sequence; or a succession of levels separately
25 measured for media-point responses during a preliminary
26 precalibration scan.

27 When one of these interpolation models is used, then
28 further preferably the preliminary precalibration scan is
29 not made automatically in field operations but only at the
30 factory. An alternative preference is that the prelimi-
31 nary precalibration scan be made automatically in field
32 operations — but not applied in absolute terms, and that
33 rather it be used only for proportioning the interpolation

1 between the two responses obtained at the ends of each
2 sequence of patches.

3 When the applying step includes adjusting the sensor
4 response to substantially each color patch in substantial-
5 ly all the patterns — as described above — then prefera-
6 bly the printing step includes automatically arranging
7 some of the patch sequences for each test pattern to fit
8 an available size of the medium. For this purpose the
9 sequences may be arranged either side-by-side or one above
10 the other on the printing medium. Here the disposition of
11 each sequence between two unprinted areas is maintained —
12 and also the steps of exposing the two adjoining unprinted
13 areas, and interpreting the two sensor unprinted-adjoin-
14 ing-area responses, are maintained — notwithstanding the
15 automatic arranging. In this way the method is made ro-
16 bust to use of different printing-medium sizes.

17 When such automatic arranging is used, preferably the
18 printing step includes printing the patches, within each
19 sequence, in alternation between two extreme thitherto-un-
20 printed tonal values of the sequence. In consequence, for
21 each colorant — to provide a roughly constant printing
22 activity during the printing step — highest and lowest
23 tones appear side by side at one end of each sequence, and
24 two closest-valued middle tones appear side by side at an
25 opposite end of each sequence.

26 An alternative to the sequencing described in the
27 preceding paragraph is that the printing step include
28 printing the patches, within each sequence, in alternation
29 between two most-nearly-central thitherto-unprinted tonal
30 values of the sequence. The point is that, for each col-
31 orant, a roughly constant printing activity is provided
32 during the printing step: two closest-valued middle tones
33 appear side by side at an one end of each sequence, and

1 highest and lowest tones appear side by side at an oppo-
2 site end of each sequence.

3 Another basic preference is that the printing step
4 include scanning at least one marking printhead along the
5 scanning direction. This step forms the test pattern.
6
7

8 In preferred embodiments of its second major indepen-
9 dent facet or aspect, the invention is an apparatus for
10 printing an image hardcopy on a printing medium. This ap-
11 paratus includes at least one printhead for marking on the
12 medium, and a processor for controlling the at least one
13 printhead to discharge inkdrops in a pattern to form the
14 image.

15 Also included are some means for color-calibrating
16 the at least one printhead. For purposes of breadth and
17 generality in discussing the invention, these means will
18 be called the "color-calibrating means" or simply the
19 "calibrating means".

20 These calibrating means include several subelements,
21 namely:
22

23 portions of the processor for operating the at least
24 one printhead and the carriage to form a color-
25 calibration test pattern, the test pattern being
26 formed on the medium adjacent to at least one
27 reference area,
28

29 at least one light source for scanning across the
30 test pattern and the at least one area to illu-
31 minate the pattern and the at least one area,
32

33 a sensor for scanning across the pattern and at least
34 one area, with the at least one source, to mea-

1 sure illuminated colors in the test pattern and
2 the at least one area, and
3
4 some means for interpreting measurement signals from
5 the sensor, to correct the sensor output signals
6 for drift due to incomplete warmup.
7

8 These last-mentioned means, again for generality and
9 breadth, will be called the "interpreting means".

10 The interpreting means include processor portions for
11 performing two functions: isolating measurement-signal
12 segments representing the at least one area to establish a
13 tonal-reference calibration level, and applying the cali-
14 bration level to correct the measurement signals due to
15 the measured illuminated colors.
16

17 The foregoing may represent a description or defini-
18 tion of the second aspect or facet of the invention in its
19 broadest or most general form. Even as couched in these
20 broad terms, however, it can be seen that this facet of
21 the invention importantly advances the art.

22 In particular, even if the measurement signals are
23 intrinsically unreliable due to either the light source or
24 detector still warming up during the measurement, never-
25 theless the signals can be rendered fully reliable. This
26 is achieved by the simple provision of reference area(s)
27 and the interpreting means.
28

29 Although the second major aspect of the invention
30 thus significantly advances the art, nevertheless to
31 optimize enjoyment of its benefits preferably the inven-
32 tion is practiced in conjunction with certain additional
33 features or characteristics. In particular, preferably
34 the apparatus further includes a scanning carriage for

1 carrying the at least one printhead across the medium to
2 form the image. Here the processor includes components
3 for coordinating the carriage and the at least one print-
4 head to form the image.

5 Another basic preference is that the light source
6 include a light-emitting diode. Yet another is that the
7 interpreting means include an analog-to-digital converter
8 (ADC) for receiving the measurement signals and deriving
9 therefrom converter output signals representing the mea-
10 surement signals; and portions of the processor for inter-
11 preting the converter output signals, to correct the con-
12 verter output signals for drift due to incomplete warmup.

13 Still another basic preference is that each reference
14 area be an unprinted area of the printing medium. In this
15 way the tonal-reference calibration level is made a medi-
16 um-point calibration level.

17 If the reference areas are unprinted areas, then
18 preferably the at least one reference area includes plural
19 unprinted areas of the printing medium; and the test
20 pattern is formed on the medium between at least two of
21 the plural unprinted areas. Another general preference is
22 that the at least one printhead include plural printheads.

23 When an ADC is in service as mentioned above, the at
24 least one reference area preferably includes plural such
25 areas. The test pattern then is formed on the medium be-
26 tween at least two reference areas.

27
28
29 In preferred embodiments of its third major indepen-
30 dent facet or aspect, the invention is in particular an
31 economical apparatus. It is for printing an image hard-
32 copy on a printing medium, and for obtaining near-colori-
33 metric quality although the apparatus has inexpensive
34 components. (As will be understood, the phrase "near-col-

1 orimetric" may encompass reasonably accurate measurement
2 results obtained through procedures such as the Baker doc-
3 ument characterizes as "pseudodensitometric".)

4 The apparatus includes at least one printhead for
5 marking on the medium. The at least one head is subject
6 to marking tolerances that require color calibration:
7 this is the first of several problems that characterize
8 some of the elements of the invention.

9 Also included is at least one processor. The proces-
10 sor has portions for controlling the at least one print-
11 head to discharge inkdrops in a pattern to form the image.

12 In addition the apparatus includes some means for
13 color-calibrating the at least one printhead. As before
14 these will be called the "color-calibrating means" or just
15 "calibrating means".

16 These means include portions of the processor for
17 operating the carriage and at least one printhead to form
18 a color-calibration test pattern. The pattern is formed
19 on the printing medium adjacent to at least one reference
20 area (of the printing medium) that provides a tonal-ref-
21 erence calibration level.

22 The calibrating means also include plural light-
23 emitting diodes for scanning across the test pattern and
24 the at least one reference area to illuminate the pattern
25 and the at least one area. Temperature dependence in the
26 diodes leads to drift of illumination level during warmup:
27 this is another of the several problems mentioned above.

28 In addition the color-calibrating means include a
29 sensor for scanning across the pattern and at least one
30 area. The at least one sensor is scanned together with
31 the diodes, to measure illuminated colors in the test
32 pattern and to measure the at least one reference area.
33 As a result the illumination drift leads to drift of meas-
34 urement signals from the sensor.

1 The calibrating means further include an ADC for
2 receiving the measurement signals. Nonlinearities in this
3 converter make measurements of small signal differences on
4 a large signal pedestal undesirable. This fact sets the
5 stage for yet another of the several problems: as a re-
6 sult of these nonlinearities, and the undesirability of
7 having the small signal differences superposed on a large
8 signal, the diodes are used in alternation rather than
9 continuously — and therefore they never fully complete
10 warmup. Because they never fully warm up, in turn they
11 drift during each operating cycle.

12 The calibrating means also include some means for
13 compensating for incomplete diode warmup. For the reasons
14 noted earlier, these last-mentioned means will be called
15 the "compensating means".

16 The compensating means include portions of the proc-
17 essor, used for interpreting output signals from the con-
18 verter, to correct the converter output signals for drift
19 due to the incomplete warmup. These interpreting portions
20 in turn include processor portions for isolating conver-
21 ter-signal segments representing tonal-reference calibra-
22 tion level, and applying the tonal-reference calibration-
23 level segments to correct the measurement signals due to
24 the measured illuminated colors.

25 Thereby the apparatus accommodates the printhead tol-
26 erances and diode temperature dependence, and avoids the
27 converter nonlinearities. In this way the invention it-
28 self resolves the several problems noted above.

29
30 The foregoing may represent a description or defini-
31 tion of the third aspect or facet of the invention in its
32 broadest or most general form. Even as couched in these
33 broad terms, however, it can be seen that this facet of
34 the invention importantly advances the art.

1 In particular, the problems discussed arise from use
2 of inexpensive components, but the invention resolves all
3 those problems. Hence the invention enables achievement
4 of superior performance by an inexpensive apparatus.

5
6 Although the third major aspect of the invention thus
7 significantly advances the art, nevertheless to optimize
8 enjoyment of its benefits preferably the invention is
9 practiced in conjunction with certain additional features
10 or characteristics. In particular, preferably the appara-
11 tus further includes a scanning carriage for carrying the
12 at least one printhead across the medium to form the im-
13 age.

14 In this case the at least one processor also has
15 portions for coordinating the carriage and the at least
16 one printhead to form the image. The processor control-
17 ling portions include portions for performing calculations
18 used respectively in these functions:

19
20 color corrections to image data if desired,

21
22 rendition to exchange resolution for color depth,

23
24 ink depletion to avoid placement of excessive col-
25 orant on the printing medium, and

26
27 printmasking to allocate inkdrop discharge as between
28 successive scans of the scanning carriage.

29
30 Another preference is that the processor operating
31 portions include some means for printing the test pattern
32 in each of plural colors respectively, and for each color
33 as a sequence of color patches at various tonal levels;
34 and that the processor interpreting portions include some

1 means for applying the sensor reference-area measurements
2 to adjust the sensor measurement for substantially each
3 color patch in at least one of the plural test patterns.

4 When the provisions described in the preceding para-
5 graph are present, it is also preferable that the applying
6 means include some means for applying the sensor refe-
7 rence-area measurements to adjust the sensor measurement
8 for substantially each color patch in substantially all of
9 the plural test patterns. As before, these will be called
10 the "applying means".

11 When such applying means are included, preferably
12 they in turn include some means for interpolation between
13 two sensor reference-area responses obtained at ends of
14 each sequence of patches. In this case a still further
15 preference is that the interpolation be based upon an in-
16 terpolation model that is either an assumed mathematical
17 function interrelating responses at ends of each sequence
18 with scan positions within each sequence; or a succession
19 of levels separately measured for media-point responses
20 during a preliminary precalibration scan.

21 For this last-mentioned case there are several optio-
22 nal features, some of which also have been mentioned ear-
23 lier. Preferably:

- 24
- 25 ■ the preliminary precalibration scan is not made auto-
26 matically in field operations — only at the factory;
- 27
- 28 ■ the preliminary precalibration scan is made automati-
29 cally in field operations but is not applied in abso-
30 lute terms, and rather is used only for proportioning
31 interpolation between two responses obtained at ends
32 of each sequence of patches; and
- 33

- 1 ■ the processor operating portions include means for
2 printing the patches, within each sequence, in alter-
3 nation between two extreme thitherto-unprinted tonal
4 values of the sequence — so that, for each color, to
5 roughly stabilize the temperature of an associated
6 printhead:

7
8 highest and lowest tones appear side by
9 side at one end of each sequence, and

10
11 two closest-valued middle tones appear side
12 by side at an opposite end of each
13 sequence; or

- 14
15 ■ the processor operating portions include means for
16 printing the patches, within each sequence, in alter-
17 nation between two most-nearly-central thitherto-
18 unprinted tonal values of the sequence — so that,
19 for each color, to roughly stabilize the temperature
20 of an associated printhead:

21
22 two closest-valued middle tones appear side
23 by side at an one end of each
24 sequence, and

25
26 highest and lowest tones appear side by
27 side at an opposite end of each
28 sequence.

29
30 In preferred embodiments of its fourth major indepen-
31 dent facet or aspect, the invention is an apparatus for
32 printing an image hardcopy on a printing medium. The ap-
33 paratus includes at least one printhead for marking on the
34 medium; and a processor for controlling the at least one

1 printhead to discharge inkdrops in a pattern to form such
2 image.

3 It also includes some means for color-calibrating the
4 at least one printhead. These means (for breadth and
5 generality called the "calibrating means") include por-
6 tions of the processor for operating the at least one
7 printhead to form a color-calibration test pattern on the
8 medium.

9 The calibrating means also include at least one light
10 source for scanning across the test pattern to illuminate
11 the pattern at plural scan positions; and a sensor for
12 scanning across the pattern, with the at least one source,
13 to measure illuminated colors at the scan positions. Also
14 included are guide means that establish a spacing between
15 the printing medium and at least a portion of the sensor;
16 the guide means are subject to tolerances that lead to
17 nonuniformity of the spacing, at the scan positions.

18 Further included in the calibrating means are some
19 means for interpreting measurement signals from the sen-
20 sor. These interpreting means correct the sensor output
21 signals for variation due to the spacing nonuniformity.

22 The interpreting means furthermore include processor
23 portions for:

24
25 also scanning the sensor across an unprinted region
26 of the medium to obtain respective unprinted-
27 medium tonal-reference calibration levels for
28 the scan positions,

29
30 isolating measurement-signal segments representing
31 the tonal-reference calibration levels for the
32 scan positions, and
33

1 applying the isolated signal segments to correct the
2 measurement signals due to the measured illumi-
3 nated colors.
4

5 The foregoing may represent a description or defini-
6 tion of the fourth aspect or facet of the invention in its
7 broadest or most general form. Even as couched in these
8 broad terms, however, it can be seen that this facet of
9 the invention importantly advances the art.

10 In particular, this aspect of the invention resolves
11 the problem of color-calibration error arising from tol-
12 erances in mechanical guideways and the like. This type
13 of error, as previously suggested, afflicts even relative-
14 ly expensive, highest-quality products — particularly on
15 account of their extremely extended scan axis, which is
16 provided to enable printing very large images.
17

18 Although the fourth major aspect of the invention
19 thus significantly advances the art, nevertheless to
20 optimize enjoyment of its benefits preferably the inven-
21 tion is practiced in conjunction with certain additional
22 features or characteristics. In particular, preferably
23 this facet of the invention is practiced in conjunction
24 with those discussed previously, and also with the pref-
25 erences mentioned for those earlier-discussed facets.
26
27

28 All of the foregoing operational principles and
29 advantages of the present invention will be more fully
30 appreciated upon consideration of the following detailed
31 description, with reference to the appended drawings, of
32 which:
33
34

1 BRIEF DESCRIPTION OF THE DRAWINGS

2
3 Fig. 1 is a graph of representative finished calibra-
4 tion curves for four colorants;

5 Fig. 2 is a diagram showing a preferred test-pattern
6 of four printed tonal ramps in the same four colorants,
7 for use in or as part of preferred embodiments of the
8 present invention;

9 Fig. 3 is a like diagram showing various possible
10 automatically generated configurations of the Fig. 2 test-
11 pattern ramps;

12 Fig. 4 is a flow chart showing relationships among
13 primary, simplified steps of the preferred method;

14 Fig. 5 is an elevational drawing, in longitudinal
15 section, for a line sensor used in preferred embodiments
16 of the invention;

17 Fig. 6 is a reproduction of an automatically genera-
18 ted graph of signal strengths corresponding to measured
19 light intensities reflected from certain successive fea-
20 tures of the Fig. 2 test pattern;

21 Fig. 7 is a like graph of light intensities reflected
22 from an unprinted area of printing medium, as a function
23 of time;

24 Fig. 8 is a graph similar to Fig. 7 but made under
25 different measurement conditions;

26 Fig. 9 is a block diagram, highly schematic, repre-
27 senting hardware (including programmed circuitry) in a
28 preferred embodiment of the invention;

29 Fig. 10 is a timing diagram representing signals in
30 such hardware;

31 Fig. 11 is a like diagram but for a related printing
32 system (not prior art) that is different from that of the
33 drift-related forms of the invention (but related to the
34 runout-related forms); and

Fig. 12 is an isometric or perspective view of a scan mechanism that carries printheads across the printing medium in the Fig. 9 system — particularly showing guide and support bars associated with the sensor runout.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

1. STABILITY VS. LINEARITY VS. COST

As noted in the earlier "Background" section of this document, the problem left unsolved for relatively inexpensive printing systems was how to more economically provide signal linearity and discrimination that are adequate for a good color calibration. It is also observed there that an inexpensive ADC could be sufficient if a lower standard of linearity could be tolerated, and in turn that such a system would accomplish the goal if only the overall light level could be made half as high.

Halving the illumination level, however, seemed to fly in the face of a requirement for full spectral illumination, with ample warmup time. Illumination over the full spectrum cannot be achieved by running just one LED.

On the other hand, operating only one source at a time — i. e. alternating two LEDs, with adequate warmup in each ramp-measurement cycle — would take a prohibitively long time for all the lamp-warmup intervals. The invention, however, avoids the necessity to wait for lamp warmup.

1 Preferred embodiments of the invention as described
2 in the above "Summary" section — by acquiring a reference
3 measurement in intimate association with each set of test-
4 pattern patches — introduce a new degree of freedom into
5 the solution of the problem. Since this strategy provides
6 measurement stability on a finer time scale than otherwise
7 possible, overall stability can be made adequate even with
8 higher drift of the sensor considered alone.

9 Consequently it is possible to dispense with extended
10 warmup, and this in turn permits turning the LEDs on and
11 off, rather than running both lamps continuously. Hence
12 the invention enables reconciliation of the two ultimately
13 required characteristics of an adequate measurement system
14 — linearity and stability.

15 In particular this alternating-LED system permits en-
16 tirely satisfactory operation using a less expensive ADC
17 with considerably lower sensitivity. Whereas the previ-
18 ously mentioned concurrent system requires a twelve-bit
19 ADC, application of the present invention allows use of an
20 eight-bit device instead.

22 Turning to relatively more expensive, high-end sys-
23 tems it has also been noted in the "Background" section
24 that a very small runout in sensor-to-print-medium dis-
25 tance generates a calibration defect. In fact, this cali-
26 bration error ironically emulates some characteristics of
27 the sensor instability that underlies the calibration
28 problems in economical systems.

29 It has also been shown in the "Summary" section that
30 this runout-related calibration error can be attacked by
31 the same tactics used against sensor instability as such.
32 Thus the present invention comes into play in a salutary
33 manner for both kinds of product.

2. CALIBRATION TARGET

In short, the desired linearity and stability are attainable in combination — merely through a simple but elegant geometrical provision in the test pattern and the mode in which it is scanned. Such a configuration of the test pattern (Fig. 2) include primary CMYK ramps 103-106, and marks 131, 132 for positioning the sensor and warming up the pens.

The ramps 103-106 and warmup marks 131, 132 may be arrayed in stacked rows as shown. The illustrated test pattern has sixteen patches in each color — with a column 111 for the first tonal-value patches in all colors CMYK, then an adjacent column 112 for the second tonal-value patches, and so forth through the rest of the columns 113, 114 . . . 125, 126. (To avoid cluttering this illustration, the column callout numbers have been omitted between 114 and 125.)

The ramps, however, as shown in the illustration are preferably not inked in customary ascending or descending tonal order. Rather, in the interest of holding printhead temperatures relatively uniform during the test-pattern printing, the tonal values are placed in an alternating sequence of converging (or diverging) high and low values.

If there were only four patches, for example, an acceptable converging sequence could be: 100%, 25%, 75%, 50% — so that each adjacent tone-value pair would total to a common sum (125%, for the simplified example). As another example, for six patches a diverging sequence could be: 50%, 66⅔%, 33⅓%, 83⅓%, 16⅔%, 100% — producing a common sum of 116⅔%.

As will be understood, the tonal values need not be stepped equally. Depending on the inks, media, and types of image that are of greatest interest, the steps may be

1 selected to particularly accentuate midtones, or high-
2 lights, or shadows — as preferred.

3 Actual tonal levels for the sixteen color-patch col-
4 umns 111-126 illustrated — if it is chosen to use equal
5 tonal steps — are (in percentages): 100, $6\frac{1}{4}$, $93\frac{3}{4}$, $12\frac{1}{2}$,
6 $87\frac{1}{2}$, $18\frac{3}{4}$, $81\frac{1}{4}$, 25, 75, $31\frac{1}{4}$, $68\frac{3}{4}$, $37\frac{1}{2}$, $62\frac{1}{2}$, $43\frac{3}{4}$, $56\frac{1}{4}$, 50.
7 The corresponding alternation in sensor responses (Fig. 6)
8 for the corresponding sixteen measurement plateaus 111'-
9 126' is evident.

10 In addition to the color patches, the test pattern
11 also includes tonal-reference areas 101, 102, preferably
12 in the form of white (or, more precisely, unprinted) areas
13 or "space patches" of the print medium. These reference
14 areas are employed to, in effect, adjust a full-scale val-
15 ue of the measurement system.

16 Although the ideal tonal value for the tonal-refer-
17 ence areas 101, 102 may be zero (blank printing medium),
18 it is permissible to print a well-defined nonzero tone in
19 these areas. Such a tone might for example be a light
20 gray printed with black ink, or might even be a chromatic
21 light color.

22 The illustration shows the target description paramet-
23 ers in a target of four colors, one color per row and
24 sixteen patches per color. All of these parameters, how-
25 ever, are subject to definition at the system designer's
26 preference:

27
28 width 109, 129 of each warmup mark,
29 width 127 of each space patch,
30 width 128 of each color patch,
31 height 108 of the patches and marks,
32 spacing 107 between rows of patches,
33 number (most typically from one to four) of
34 colors per row,

1 number (typically from three to six) of colors,
2 number (most typically from eight to twenty-
3 four) of patches per color,
4 list of patches for each color, with the ink
5 density of each patch, and
6 ink density (most typically 40% to 60%) of the
7 mark patch.

8
9 As will be understood, the warmup marks 131, 132 need
10 not have the same dimensions as the color patches 103-106.
11 Similarly, not all the color patch dimensions 128, 108,
12 row spacings 107 etc. need be common to the various colors
13 or tonal values.

14 In the preferred system, the printer automatically
15 detects the size of the printing medium and forms the lay-
16 out that best fits on it. In this way, both scanning time
17 and consumption of printing media are minimized.

18 Based on this technique, given a sixteen-patch, four-
19 color system, it is possible to use any one of four con-
20 figurations. Thus the system may employ:

- 21
22 ■ a layout 133 (Fig. 3) with all the ramps 106-103 in a
23 single row, or
- 24
25 ■ a layout 134 with the first three ramps 106-104 in
26 one row and the remaining ramp 103 in a separate row,
27 or
- 28
29 ■ a layout 135 with two ramps 106, 105 in a first row
30 and the remaining two ramps 104, 103 in a second, or
- 31
32 ■ a layout 136 (e. g. like Fig. 2) with each ramp in a
33 separate row.

1 Each of these configurations offers the linearity, stabil-
2 ity and economy benefits of the invention.

3 4 5 3. PROCEDURE

6
7 In operation, a target is printed 151 (Fig. 4) using
8 one of these configurations and then is scanned 152 using
9 the line sensor (Fig. 5) provided in the printer. Densi-
10 tometric or pseudodensitometric measures are then obtained
11 from the line-sensor readings, and from those the neces-
12 sary corrections for calibration are derived 153 and ap-
13 plied 154.

14 In preferred embodiments of the invention, the line
15 sensor is a measuring device, contained within a protec-
16 tive enclosure 141 (Fig. 5). The sensor includes two
17 lamps — one blue LED 143 and one amber LED 144 — and one
18 photodiode 145 that serves as the detector. For highest
19 signal-to-noise ratio, the cyan ramp 103 is measured with
20 the amber LED 144 and other colors with the blue LED 143.

21 The device preferably includes an air-cooled lens
22 146, and an infrared filter 147 that also serves as an
23 aerosol shield. The assembly is typically carried with
24 the pens, on a pen carriage, and disposed to illuminate
25 and read the printing medium 142 (such as paper, or a
26 plastic web, or glossy or coated stock, all as very well
27 known in the art). The print medium 142 is usually sup-
28 ported by a platen 148.

29 Before starting the scan, the line sensor itself is
30 calibrated to maximize the signal range and further stabi-
31 lize the measurement. That sensor calibration should not
32 be confused with the overall color calibration which is
33 the subject of the present invention.

1 One suitable sensor-calibration paradigm is described
2 in the above-mentioned Subirada patent document. The
3 principles asserted in that document, however, need not be
4 followed in practicing the present invention.

7 4. TRIGGERING EVENTS

9 In order to obtain best color reproduction, the col-
10 or-calibration algorithm should be performed whenever the
11 printer varies. Such variation can be, for example, a
12 change in pens, printing medium, or humidity. The user of
13 the printer system can trigger the calibration manually
14 whenever desired.

15 The greatest single contribution to color-calibration
16 shift is produced by changing pens. When this occurs, in
17 the preferred embodiment, automatically the system asks
18 the user to perform the calibration — which, if the user
19 complies, consumes a quantity of printing medium, ink and
20 time.

21 If the user decides in favor of this recommended re-
22 calibration, the new calibration values will be used until
23 the next trigger event — i. e. pen change, manual cali-
24 bration or calibration reset. If the user decides against
25 recalibrating, default factory values are used instead.

28 5. MEASUREMENT

30 The target (test pattern) is scanned with the line
31 sensor (or if preferred a true colorimeter as taught by
32 Baker), to acquire raw signal values 101', 102', 131',
33 132', 111'-126' (Fig. 6). In the illustration the ab-
34 scissa represents position along the carriage scan axis;

1 and the series of alternating high and low plateaus ap-
2 pearing in the chart are signal values obtained at succes-
3 sive positions along that axis.

4 Close examination of the recorded waveform reveals
5 considerable noise in the signal at its plateaus, particu-
6 larly at higher signal levels where noise is intrinsically
7 higher. Also the inexpensive electronic components se-
8 lected are particularly susceptible to short-term jitter
9 as well as the drifts discussed previously.

10 Light reflected from each patch 111-126 or tonal ref-
11 erence area 101, 102 of the test pattern is recorded at a
12 corresponding one of the short, roughly horizontal pla-
13 teaus 111'-126', 101', 102' appearing in the chart. (The
14 reference number used for each plateau is the same as the
15 number for its respective patch or reference area, but
16 with the addition of a so-called "prime" symbol — i. e.
17 tick mark.)

18 In view of the noisiness just mentioned, averaging
19 within each plateau is needed. From a 24 dot/mm (600 dpi)
20 scan, roughly sixty samples (definable) of ADC output from
21 each plateau are averaged to obtain the measurement of the
22 respective patch. The present inventors call these data
23 the "absolute colorimetric ratio" or ACR, and with n rep-
24 resenting the number of samples (e. g. as just indicated
25 n ≈ 60):

26
27
$$ACR = \frac{1}{n} \sum_{x=1}^n v(x),$$

28 where $v(x)$ is the output voltage of the sensor.
29

30 To make the system less sensitive to line-sensor
31 variations (aging, aerosol contamination, different bat-
32 ches and so forth), the measurement range is rescaled be-
33 tween the print-medium sample (nominally white) and the

1 darkest patch (one hundred percent ink). These rescaled
2 data are called the "local contrast ratio" or LCR:

3
$$LCR(i) = \frac{ACR(i) - ACR_{100\%}}{ACR_{0\%} - ACR_{100\%}}$$

4
5 where i identifies a set of n values ACR ,
6 $ACR_{0\%}$ is the printing - medium measurement,
7 and $ACR_{100\%}$ is the measurement with 100% ink.
8

9 The converging profile of high and low plateaus that
10 is conspicuous in the illustration corresponds to the al-
11 ternating high and low tonal values of the patches (Figs.
12 2 and 3). As mentioned previously, the test patches are
13 printed in this way to roughly stabilize the amount of
14 printing done per unit time — and therefore the extent of
15 heating to which the pens are subjected — during the
16 course of the measurement.

17 Each set " i " of n values $ACR(i)$ is very closely
18 associated, as a group of values all taken at just a
19 particular one of the high or low plateaus — and thus
20 very closely grouped together along the carriage-scan ax-
21 is. Accordingly the index i can be regarded as a counter
22 roughly representing position along that scanning axis.

23 In this preliminary conceptual formulation, only one
24 printing-medium measurement $ACR_{0\%}$ comes into the LCR ex-
25 pression above. Here a single print-medium sample is used
26 for all patches, placing a sometimes unrealistic demand
27 upon accuracy of that single print-medium return. As will
28 next be seen, this approach is often inadequate or only
29 marginally adequate.
30
31

6. RESIDUAL SENSOR DRIFT, AND COMPENSATION

Although in the economical products discussed earlier the LEDs have been warmed up briefly to stabilize the illumination and the detector readings, typically some variability (Figs. 7 and 8) still appears within a scan. The charts illustrated are reproductions of 50 cm (20 inch) scans of raw medium — *i. e.* unprinted print-medium surface. (In other words, these sets of readings do not show reflectance from any printed color ramp or patch.)

For Fig. 7, the measurement 161 at the start (left end) is roughly eight or nine counts (three percent) higher than that 162 at the conclusion (right end). To compensate for such drifts this return 101', 102' (Fig. 6) from the medium 101, 102 — at least at one end of the scan region, preferably at both — is measured, as part of the calibration scans, concurrently with the measurement of optical returns 111'-126' from the patches 111-126.

Sensor drift can be predicted 163, 163' (Figs. 7 and 8) with less than one-percent error relative to actual drift 164, 164' — that is to say, much more accurately than just assuming that the response is stable. Such prediction enables treatment of the above-mentioned printing-medium measurement $ACR_{0\%}$ as a function of position along the carriage scan axis — so that the notation can be changed to $ACR_{0\%}(i)$, explicitly identifying the absolute contrast ratio by the position-counter index i mentioned earlier.

Once the print-medium brightness is thus expressed as a function of scan position, it follows that — in finding normalized LCR values as introduced above — each printed color patch $ACR(i)$ can be more-precisely normalized to a respective printing-medium measurement $ACR_{0\%}(i)$, rather

1 than to a single universal value applied over the entire
2 scan:

$$3 \quad LCR(i) = \frac{ACR(i) - ACR_{100\%}}{ACR_{0\%}(i) - ACR_{100\%}} .$$

4
5 Now it must be asked how to find the $ACR_{0\%}(i)$ values for
6 use here in the denominator.

7 Given the starting position 161 (Fig. 7) and knowing
8 a representative overall sensor drift to the final posi-
9 tion 162, found from a large number of overall drift
10 assessments, a full series 163 of estimated print-medium
11 brightnesses $ACR_{0\%}(i)$ can be generated by simple linear
12 interpolation. In practice this straightforward expedient
13 has been found satisfactory; however, other methods can be
14 used instead.

15 For example, still within the tactic of mathematical
16 interpolation, another interpolation function — e. g. ex-
17 ponential rather than linear — can be assumed. In some
18 cases such a function may be found to correspond to the
19 actual drift behavior much more accurately than a linear
20 function.

21 A still more accurate approach is to actually measure
22 a representative relationship among sensed returns 163'
23 (Fig. 8) from the printing medium, at carriage-scan posi-
24 tions corresponding to the intermediate patch positions i
25 — that is, between the starting and ending positions
26 161', 162', rather than at those two positions alone.
27 Such a measured relationship then serves as an ad hoc
28 interpolation "function" for use in finding the series
29 $ACR_{0\%}(i)$ of print-medium brightnesses.

30 For this purpose, an extra scan (not shown) can be
31 used to actually measure the print medium at the exact
32 points along the scan axis where the patches appear — but
33 not, of course, at the identical two-dimensional locations
34 where and times when the patches are present. For exam-

1 ple, such an extra measurement scan can be performed
2 before the test-pattern patches are printed, or can be
3 performed at a height along the print-medium advance axis
4 that is above or below the patches. The extra scan is
5 valuable in finding a time-variation profile of short-term
6 relative drift, within a measurement period, that is like-
7 ly to be somewhat reproducible.

8 Even if this is done, however, because of ongoing
9 longterm drift that changes the absolute level of the
10 whole profile it is not fully a substitute for printing
11 and measuring the reference areas at the end or ends of
12 the color ramps — to obtain a good correlation between
13 the color scan and the print-medium scan. Use of the
14 real-time returns from both ends 101, 102 (Fig. 6) of the
15 test pattern is more definitive of the absolute level.

16 On the other hand, as stated above, in fact a sensor
17 relative drift profile within a scan, such as illustrated
18 (Figs. 7 and 8), is moderately reproducible. Accordingly
19 calibration based on measuring even just one end (e. g.
20 just the starting level 101) — and then thereafter peg-
21 ging or anchoring the measured drift profile to the value
22 101', 161/161' measured there — is usually a good approx-
23 imation to the calibration based on measuring at both ends
24 101, 102.

25 The purpose of anchoring the profile, as just men-
26 tioned, is to ensure the correct absolute tonal level. In
27 economical products, once again, error in absolute level
28 is the greater component of the calibration errors that
29 the invention aims to solve — whereas the time-variation
30 profile may usually be considered in essence a refinement.
31 (The contrary will generally be found true in runout-rela-
32 ted problems of the higher-end systems.)

33 For any newly designed system, it is advisable to
34 verify the adequacy of this approximation. In the most

1 highly preferred embodiment, in view of the uncertainty
2 that is associated with shifts in operating characteris-
3 tics during the course of a printer model-line production
4 run, measurement is made at both ends.
5

6 In practice of this invention, the distinctions be-
7 tween what is "measured", what is "predicted" and what is
8 "actual" may be confusing. The curve of values 163' phys-
9 ically measured at the carriage-scan-axis positions of the
10 color patches — but measured at very different heights,
11 along the media-advance axis, from those color patches —
12 is labeled "predicted" because it represents numbers that
13 will be used for predicting future print-medium tonal val-
14 ues at the two-dimensional positions (i. e. coordinates)
15 of the color patches.

16 The curve of values 164' derived from those "predic-
17 ted" values is labeled "actual" because it represents num-
18 bers that are believed to be true underlying tones of bare
19 printing medium, at those two-dimensional positions of the
20 patches. Since the patches by definition occupy those
21 positions during measurement scans, no real-time direct
22 measurement of the "actual" values is physically possible.
23

24 Referring again to the above expression for LCR: not
25 only the bare-print-medium returns ACR_{0%}(i) but also the
26 full-inking returns ACR_{100%}(i) could be estimated as well.
27 Their influence, however, is much smaller, both because of
28 the equation form and because of the lower physical varia-
29 tion (less light is reflected in a 100% patch).

30 Sensor-drift compensation is performed on a per-color
31 basis. Hence it is immaterial whether the test patterns
32 are printed each on its own individual line or strung out
33 in groups of two or more on a line.

1 In the most highly preferred embodiment, the patches
2 are printed with equal tonal spacing — i. e. in colori-
3 metrically uniform steps. Other tonal spacings in the
4 ramp, however, can be used to equivalent effect.

7. RUNOUT-INDUCED CALIBRATION ERROR, AND COMPENSATION

5
6
7
8
9 Although the presentation in the preceding subsec-
10 tions has been introduced in terms of sensor instability
11 as a root cause, it can now be appreciated that virtually
12 identical observable anomalies are generated when sensor
13 proximity to the printing medium varies along the scan
14 path. Specifically, even when the light sources and de-
15 tector in the sensor are stable — and even when the fol-
16 lowing electronic components are linear — the simple
17 variation of distance from source to print medium, and
18 back to detector, causes a corresponding variation of cal-
19 ibration signal.

20 Accordingly the same analysis applies to compensating
21 for this variation through measurement of the bare, un-
22 printed medium at positions across the scan axis — and
23 application of the resulting offsets to the respective raw
24 data points at like positions. In particular, however,
25 since runout may be most typically worst in central re-
26 gions along the carriage track than at one end or the
27 other, here the use of linear interpolation 163 (Fig. 7)
28 is less likely to be adequate.

29 Instead the use of actually measured relationships
30 163' (Fig. 8) among the measured points is the solution
31 most typically favored for this cause of calibration anom-
32 alies. In this case it is the particular profile of those
33 relationships that carries the crux of the improvement.
34 Since the sensor itself is amply stable, the previously

1 mentioned anchoring of the profile (to obtain the correct
2 photometric level) usually is unnecessary.

3 4 5 8. HARDWARE AND PROGRAM IMPLEMENTATION 6

7 As the invention is amenable to implementation in, or
8 as, any one of a very great number of different printer
9 models of many different manufacturers, little purpose
10 would be served by illustrating a representative such
11 printer. If of interest, however, such a printer and some
12 of its prominent operating subsystems can be seen illus-
13 trated in several other patent documents of the assignee,
14 Hewlett Packard — such as for example the previously men-
15 tioned document of Thomas Baker or that of Antoni Gil Mi-
16 guel, which both particularly illustrate a large-format
17 printer-plotter model.

18 In some such representative printers, a cylindrical
19 platen 241 (Fig. 9) — driven by a motor 242, worm and
20 worm gear (not shown) under control of signals from a
21 digital electronic processor 71 — rotates to drive sheets
22 or lengths of printing medium 4A in a medium-advance di-
23 rection. Print medium 4A is thereby drawn out of a supply
24 of the medium and past the marking components that will
25 now be described.

26 A pen-holding carriage assembly 220 carries several
27 pens, as illustrated, back and forth across the printing
28 medium, along a scanning track — perpendicular to the
29 medium-advance direction — while the pens eject ink. For
30 simplicity's sake, only four pens are illustrated; how-
31 ever, as is well known a printer may have six pens or
32 more, to hold different colors — or different dilutions
33 of the same colors as in the more-familiar four pens. The

1 medium 4A thus receives inkdrops for formation of a de-
2 sired image.

3
4 A very finely graduated encoder strip 233, 236 is ex-
5 tended taut along the scanning path of the carriage assem-
6 bly 220 and read by a very small automatic optoelectronic
7 sensor 237 to provide position and speed information 237B
8 for one or more microprocessors 71 that control the opera-
9 tions of the printer. One advantageous location 35 (Fig.
10 12) for the encoder strip is immediately behind the pens.

11 A currently preferred position for the encoder strip
12 233, 236 (Fig. 9), however, is near the rear of the pen
13 carriage — remote from the space into which a user's
14 hands are inserted for servicing of the pen refill car-
15 tridges. For either position, the sensor 237 is disposed
16 with its optical beam passing through orifices or trans-
17 parent portions of a scale formed in the strip.

18 The pen-carriage assembly 220, 220' is driven in
19 reciprocation by a motor 231 — along dual support and
20 guide rails (not shown) — through the intermediary of a
21 drive belt 235. The motor 231 is under the control of
22 signals 231A from the processor or processors 71.

23 Preferably the system includes at least four pens
24 holding ink of, respectively, at least four different col-
25 ors. Most typically the inks include yellow Y, then cyan
26 C, magenta M and black K — in that order from left to
27 right as seen by the operator. As a practical matter,
28 chromatic-color and black pens may be in a single printer,
29 either in a common carriage or plural carriages.

30 Also included in the pen-carriage assembly 220, 220'
31 is a tray carrying various electronics. Fig. 9 most
32 specifically represents a system such as the Hewlett Pac-
33 kard printer/plotter model "DesignJet 2000CP", which does
34 not include the present invention. These drawings, how-

1 ever, also illustrate certain embodiments of the inven-
2 tion, and — with certain detailed differences mentioned
3 below — a printer/plotter that includes preferred embodi-
4 ments of the invention.

5 The output-printing stage discussed above with re-
6 spect to the Fig. 9 block diagram includes carriage guide
7 and support bars 32, 34 (Fig. 12), as well as end bracket
8 39. It is primarily a tiny nonlinearity in the bars 32,
9 34 that is responsible for the previously noted sensor-to-
10 print-medium runout problems in one product.

11 In that product, however, the bars are actually much
12 longer, in proportion to other relevant system dimensions,
13 than suggested in Fig. 12. Accordingly the sensor limi-
14 tations discussed earlier occur notwithstanding that the
15 carriage runout as such is held to an extremely fine
16 tolerance.

17
18 Before further discussion of details in the block
19 diagrammatic showing of Fig. 9, a general orientation to
20 that drawing may be helpful. This diagram particularly
21 represents preferred embodiments of one previously dis-
22 cussed apparatus aspect of the invention.

23 Conventional portions of the apparatus appear as the
24 printing stage 220 through 251, and 4A, discussed above,
25 and also the final output-electronics stage 78 which
26 drives that printing stage. This final-output stage 78 in
27 turn is driven by a printmasking stage 75, which allocates
28 printing of ink marks 218, 219 as among plural passes of
29 the carriage 220, 220' and pens across the medium 4A.

30 Also generally conventional are a nonvolatile memory
31 77, which supplies operating instructions 66 (many of
32 which are novel and implement the present invention) for
33 all the programmed elements; an image-processing stage 73,
34 rendition-and-scaling module 74; and color input data 70

1 seen at far left in the diagram. The data flow as input
2 signals 191 into the processor 71.

3 Features particularly related to the apparatus aspect
4 of the invention appear in the upper and upper-central re-
5 gion of the diagram as element 72, and elements 80 through
6 87; these will be detailed below. Given the statements of
7 function and the diagrams presented in this document, a
8 programmer of ordinary skill — if experienced in this
9 field — can prepare suitable programs for operating all
10 the circuits.

11
12 The novel features appear primarily in the color-
13 calibrating means 72 — which include the test-pattern-
14 generating circuitry 80, 81, as well as a data path 65 for
15 information that results from reading of the test patterns
16 by another small optical sensor 251 that also rides on the
17 carriage. This sensor is the device detailed in Fig. 5
18 and already discussed.

19 Still within the processor 71 and its calibrating
20 unit 72, such sensor data 65 pass via the previously men-
21 tioned inexpensive ADC 82 to a module 83 that reads and
22 interprets the data. In particular the interpretation
23 includes operation of a drift-compensation subunit 84.

24 It is here that the invention provides portions 85 of
25 the processor circuitry that read and adjust for the ref-
26 erence tones 101, 102 (Fig. 2). Test-pattern data re-
27 ceived from the path 65 and read by the interpreting means
28 83 are used in derivation 82 of the transfer-function data
29 87 already described.

30 One or more of various forms 87 of the transfer-func-
31 tion information — whether in the form of coefficients
32 for use in a formula, or in the form of a lookup table —
33 are then stored in a particular dedicated portion 86 of
34 the previously mentioned nonvolatile memory 77. The

1 transfer-function information is retrieved from that mem-
2 ory bank 86 whenever needed to guide the operation of the
3 color-adjustment module 76 in preparing the input data 70
4 for later transformations 74, 75, 78 and thereby for even-
5 tual printing in the printing stage.

6
7 The pen-carriage assembly is represented separately
8 at 220 when traveling to the left 216 while discharging
9 ink 218, and at 220' when traveling to the right 217 while
10 discharging ink 219. It will be understood that both 220
11 and 220' represent the same pen carriage, with the same
12 pens.

13 The previously mentioned digital processor 71 pro-
14 vides control signals 220B, 220'B to fire the pens with
15 correct timing, coordinated with platen drive control
16 signals 242A to the platen motor 242, and carriage drive
17 control signals 231A to the carriage drive motor 231. The
18 processor 71 develops these carriage drive signals 231A
19 based partly upon information about the carriage speed and
20 position derived from the encoder signals 237B provided by
21 the encoder 237.

22 (In the block diagram all illustrated signals are
23 flowing from left to right except the information 237B, 65
24 fed back from the sensors 237, 251 — as indicated by the
25 associated leftward arrows — and analogously the previ-
26 ously mentioned information 66 where shown passing to the
27 calibrating means 72, in a nonstandard direction.) The
28 codestrip 233, 236 thus enables formation of color ink-
29 drops at ultrahigh precision during scanning of the car-
30 riage assembly 220 in each direction — i. e., either left
31 to right (forward 220') or right to left (back 220).

32
33 The invention is not limited to operation in four-
34 colorant systems. To the contrary, for example six-col-

1 orant "CMYKcm" systems including dilute cyan "c" and ma-
2 genta "m" colorant are included in preferred embodiments.
3

4 The integrated circuits 71 may be distributive — be-
5 ing partly in the printer, partly in an associated compu-
6 ter, and partly in a separately packaged raster image
7 processor. Alternatively the circuits may be primarily or
8 wholly in just one or two of such devices.

9 These circuits also may comprise a general-purpose
10 processor (e. g. the central processor of a general-pur-
11 pose computer) operating software such as may be held for
12 instance in a computer hard drive, or operating firmware
13 (e. g. held in a ROM 77 and for distribution 66 to other
14 components), or both; and may comprise application-spe-
15 cific integrated circuitry. Combinations of these may be
16 used instead.
17

18 9. ADEQUATE LINEARITY WITH INEXPENSIVE CONVERTER 19

20 The reason that an inexpensive eight-bit ADC 82 can
21 provide sufficient sensitivity and linearity for good col-
22 or calibration is that the signal pedestal — or typical
23 d. c. offset — 158 (Fig. 10) in the present invention is
24 roughly half of the analogous pedestal or offset 158' in
25 the previously mentioned high-end system that originally
26 was concurrently developed without the present invention.
27 Therefore the ADC range can be scaled to just half the
28 signal range.
29

30 Generally speaking the small differences ΔLCR in pla-
31 teau signals are the same size in either system. (These
32 tiny but critical differences ΔLCR are not the steps
33

1 between tonal values in the ramp, but rather are the
2 uncontrolled variations in these steps. These small tone
3 intervals basically represent the pen tolerances, tempera-
4 ture fluctuations, and ADC sensitivity or sensitivity
5 limitations discussed earlier.)

6 Halving the overall signal range therefore doubles
7 the implication of these variances to be measured. That
8 is, it doubles the number of ADC bits corresponding to a
9 typical variance.

10
11 It remains to be seen why the invention induces the
12 low signal pedestal 158. In the concurrently developed
13 system, both the amber LED illumination 166' (Fig. 11) and
14 blue LED illumination 167' are always on.

15 Both lamps are on starting from the beginning t_0 of
16 the warmup time and proceeding through the start t_1 of the
17 cyan scan interval — and the start t_2 of the remaining
18 three scan intervals — to the conclusion t_3 of the test.
19 In that system the total illumination 168' is therefore
20 roughly twice that from each LED considered alone.

21 This is not so for the drift-correcting forms of the
22 present invention, in which the amber illumination 166 and
23 blue illumination 167 are present sequentially rather than
24 together. The total illumination 168 is therefore sub-
25 stantially the same as that from each LED considered
26 alone.

27
28 For tutorial purposes the reflectance behavior of the
29 various patches will be stated here in a very highly sim-
30 plified way, and the drawings too are very simplified.
31 The resulting conclusions remain generally instructive,
32 although the numerical details are only very rough.

33 During measurement of the cyan patch (t_1 through t_2),
34 very roughly all the illumination from the blue LED is

1 constantly reflected from that patch — and the signal
2 variations ΔLCR of interest (as well as the entire struc-
3 ture of signal steps) occur mainly in the reflection from
4 the amber LED. Hence in this interval the return 169'
5 consists of the alternating opposed-sawtooth shape seen
6 earlier, but deducted from the double-height total illumi-
7 nation 168'.

8 The drawing clearly shows the result: representative
9 variations ΔLCR of interest are raised above the zero sig-
10 nal level by the height of the roughly unattenuated blue
11 illumination. During measurement of the first two other
12 patches (from t2 two-third of the way to t3), somewhat
13 converse relationships obtain: major fractions of all the
14 amber LED output reflect constantly from the yellow and
15 magenta patches.

16 Therefore the signal varies mainly in the reflection
17 from the blue LED — once again raising representative
18 variances above the zero, by the height of the relatively
19 less-attenuated amber illumination. (The black measure-
20 ment is differently affected, as shown.)
21
22
23
24

25 The above disclosure is intended as merely exemplary,
26 and not to limit the scope of the invention — which is to
27 be determined by reference to the appended claims.